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Initial Study on a Mechanical Starting Mechanism for Two-Stroke Free Piston Engine

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ABSTRACT

The Free-Piston Engine (FPE) offers a flexible alternative to conventional Internal Combustion Engines (ICE) by allowing variable compression ratio control and eliminating the crankshaft. The advantages of FPEs lie in their simple design with fewer moving parts, resulting in a compact engine with lower maintenance costs, reduced friction losses, and improved fuel efficiency. However, the main technical challenges to adopting this technology are engine startup and stable operation. This study proposes a dual two-stroke FPE model using gasoline fuel and spark ignition. An independent starting mechanism for the FPE was developed, which does not utilize an integrated linear motor as in previous studies. The simulation results show that with a starting speed of 0.7 m/s, a starting compression ratio of 3.3, fuel injection of 3 mg, and a combustion duration of 2 ms to 5 ms, the FPE can ignite with pressures ranging from 9 bar to 11 bar. The mechanical resonance starting method was experimentally validated, achieving the desired compression ratio of 3.3, a fixed electric motor pull force of approximately 400 N over 1.4 seconds, and a piston displacement speed of about 0.7 m/s. The pressure during the startup process was around 4 bar, and the ignition process produced a peak pressure of 13 bar. The FPE model then transitioned to continuous operation over several cycles with peak cylinder pressures reaching 12 bar.

Keywords: Free-piston Engine, Mechanical Starting Mechanism, Experiment, Simulation

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1. Introduction

The Free Piston Engine Generator (FPEG) can be considered as a potential equipment for linear energy conversion. Unlike traditional internal combustion engines, by eliminating the crankshaft mechanism, FPEG uses variable linear motion instead of rotary motion. Therefore, it usually has a simple structure, with little loss in the energy conversion process due to the elimination of redundant transmission devices [1-3]. Since the lack of a crankshaft means that the FPEG does not have a fixed Top Dead Center (TDC), the compression ratio can be varied, and it can also run on a variety of fuels [4–10]. Therefore, FPEG is a potential option to expand the range of hybrid vehicles and household generators [11-13]. FPEG comes in a variety of configurations, but most are driven by the force generated from the heat release process in the cylinder, which causes the engine to move freely linearly and converts kinetic energy into electrical energy [14]. Before operating in free mode, the FPEG must complete the start-up mode. In recent years, many researchers have conducted experiments and simulations at the start of FPEG. Many studies have shown that the linear generator built into the FPEG can be used as a starting device and it can act as a linear motor to compress the gas in the cylinder to the starting pressure [15,16]. There are two popular startup strategies today "immediately switching strategy" and "gradually switching strategy" [17]. For the first strategy, the linear machine acts as an engine and produces a constant force in the direction of the piston velocity, the goal being enough pressure to ignite in just one stroke. Zulkifli [18] used a linear electric machine as a motor to start in one stroke. The higher the oscillating frequency of the piston from the bottom dead center to the top dead center (TDC), the higher the motoring force was required to drive the piston to move. Johnson et al. [19], developed the opposed-piston FPEG, an external high-pressure air source used to drive the piston, the target achieved a compression ratio in one stroke. The tests were successfully demonstrated; however, by the weak restoring force the operation of the prototype was limited to less than a minute. In most cases using the "immediately switching strategy", the capacity of the linear generator is not large enough for the pressure in the cylinder to reach the ignition pressure [20]. For the second strategy the "gradually switching strategy", a low-intensity generator provides time-varying thrust to accumulate compressed air energy based on the air spring characteristics inside the cylinder. This strategy is mainly used for current FPEG prototypes because of its more stable operation [21]. Zulkifli et al. [22,23] introduced the strategy of the resonance starting method. They simulated the resonance starting process of a spark-ignited FPEG. In the simulation model built, both a load of friction and the motor magnitude forces were regarded as constant. The simulation results showed that it is possible to achieve the required compression pressure for fuel ignition by mechanical resonance if a sufficiently large and constant force is provided to move linearly in the direction of piston motion. Jia et al [24,25], performed a resonance-starting experiment with a spark-ignited free-piston gasoline engine alternator prototype. The prototype uses the linear alternator that works as a linear motor and motor force in the direction of the piston velocity, the closed-loop control system drove this force. The resulting experiment shows that with this method the peak in-cylinder pressure and the compression ratio can be increased and then reach a stable state in some cycles. Their prototype was successfully ignited at the fourth starting cycle using a fixed thrust force of 125 N and the higher the motoring force the faster the piston speed, and the higher the in-cylinder pressure, making the engine easier to ignition.

Previous global studies have confirmed that FPE can be started resonantly by various methods but mostly by integrated linear electric machines. However, the current FPE starting systems are complex to control, difficult to control the starting force and stroke. It is necessary to propose a FPE starting mechanism that is less complex in control and has more stable stroke control. This study has developed an independent starting mechanism for FPE without using integrated linear generator "Mechanical starting mechanism". Initial simulation and experimental results show that FPE has started and operated for several cycles.

2. FPE Configuration

2.1 Prototype Specification

The FPE prototype is shown in Fig. 1. The prototype uses two 2-stroke engines, spark-ignited. The specifications of the prototype are summarized in Table 1. A mechanic structure is used to start the engine by driving the piston at a linear frequency until it reaches pressure ignition. The ignition system consisted of an ignition coil and spark plug. When the mechanical structure operates the fuel is injected into the intake manifold to form an air/fuel mixture. Then the mixture enters the auxiliary chamber during the intake stroke through the one-way valve. In scavenging, the mixture is transferred from the auxiliary chamber to the cylinder, where the compression, combustion, and exhaust processes are carried out. The ignition system consists of an ignition coil and spark plug, and the fuel injection system uses the injector, both systems are controlled by NI-USB 6212 for a more precise air-fuel ratio and ignition position.

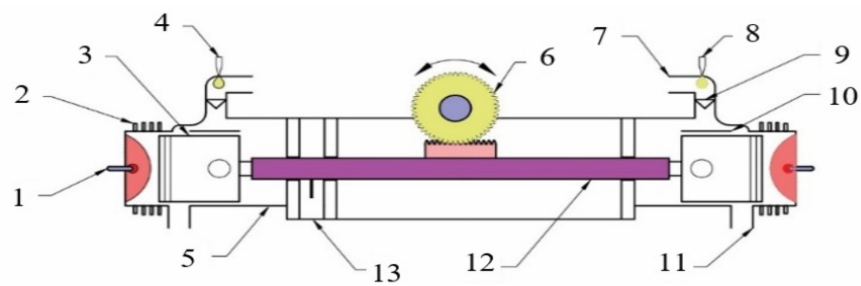

Figure 1. Schematic diagram of the FPE

1. Spark plug; 2. Cylinder; 3. Piston; 4,8. Fuel injection; 5. Scavenging chamber; 6. Mechanic starting; 7. Air-intake port; 9. One-way valve; 10. Scavenging port; 11. Exhaust port; 12. Main connection shaft; 13. Piston displacement fixed mechanism

Number of cylinders	2
Type of engine	2 stroke
Bore	34 mm
Motoring Stroke	22mm
Maximum Stroke	30 mm
Moving mass	0.5 kg
Maximun compression ratio	10.5:1
Fuel	gasoline

Table 1. Free-piston engine specifications

2.2 Description of the Mechanical Starting System

Fundamentally, the mechanical starting system for the FPE is a e mechanism, designed to ensure a 22mm piston displacement as illustrated in Fig. 2. The starting process can be divided into three phases: In the first phase, the starting mechanism still employs the principle of resonant starting, where the piston is driven at a linear frequency of 10 Hz with a constant force of 400N by an electric motor via a chain drive. The piston's displacement during this phase is constant at 22mm with a low compression ratio of approximately 3.3. In the second phase, fuel is injected into the intake port to form an air-fuel mixture, while the piston continues its linear motion, introducing the mixture into the combustion chamber through the scavenging port. Subsequently, the magnetic clutch in the mechanical starting mechanism disengages the main shaft, and the first spark immediately occurs. Finally, the FPE transitions to free-running operation with predetermined fuel injection and ignition timing. All phases are depicted in Figure 3.

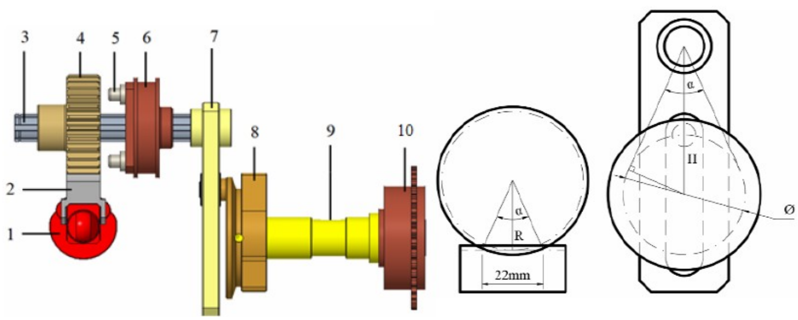

Figure 2. Mechanical starting and Coulisse mechanism

1 - Main shaft; 2 - Rack; 3 - Shaft of starting mechanism, 4 - Driven gear; 5 - Fasteners; 6 - Magnetic clutch; 7 - Handwheel; 8 - Eccentric wheel; 9 –Shaft of driven Gear; 10- Driven Gear from Starter Gear of Starter Motor

Both the fuel injection and ignition systems in this model are electronically controlled. All systems operate based on feedback from sensors. Once the starting process is complete, the FPE enters free-running operation. In this mode, both the ignition and fuel injection systems are activated, with fixed injection timing and ignition timing throughout both processes. The control system structure is shown in Figure 4.

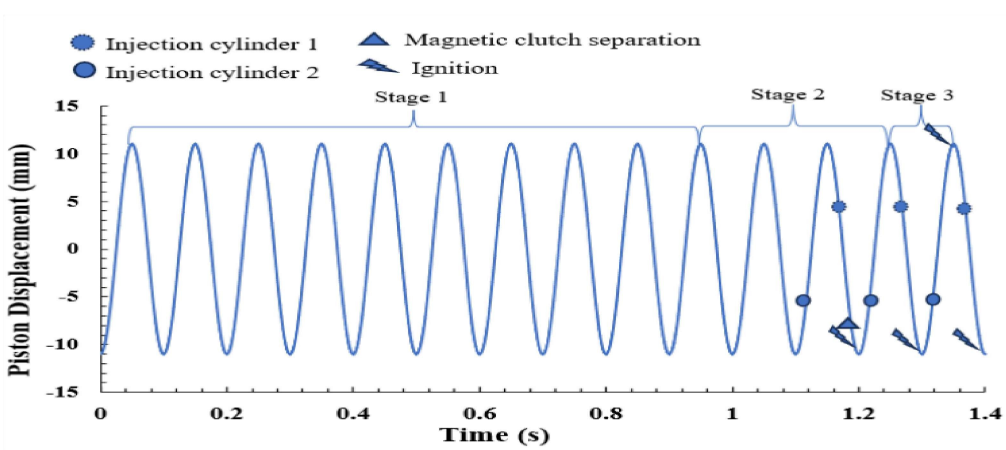

Figure 3. FPE model control method

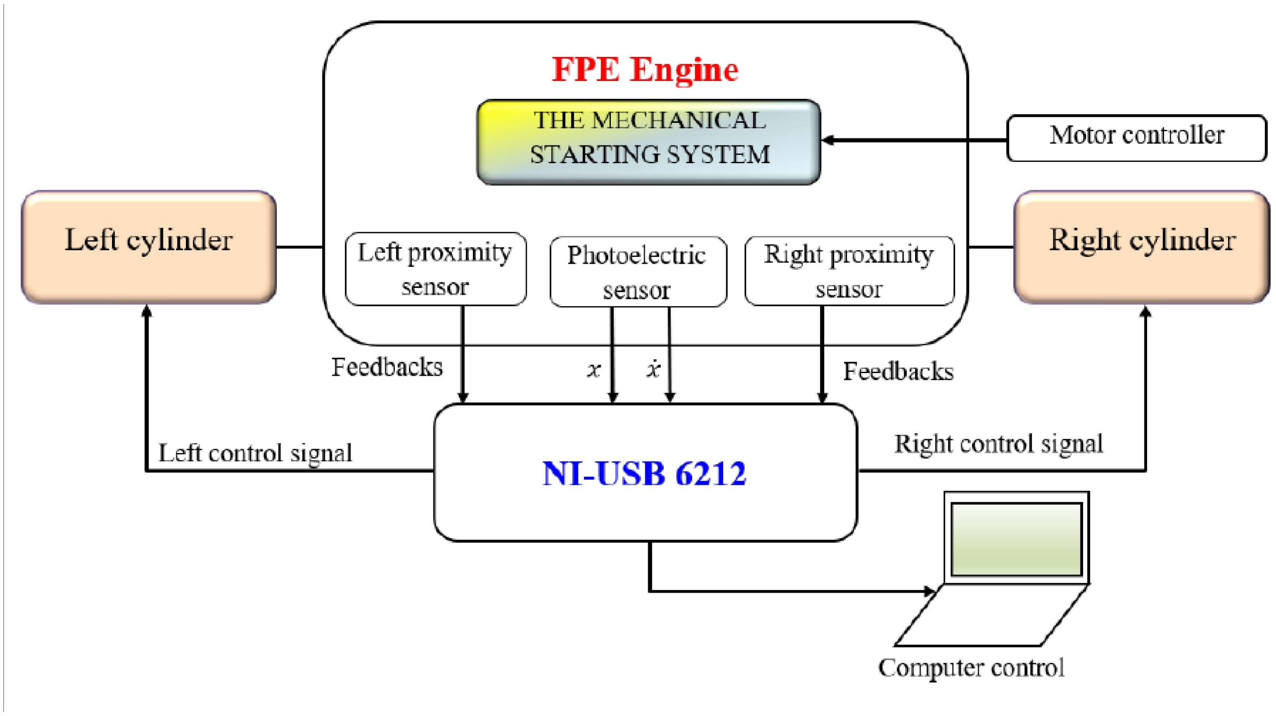

Figure 4. FPE model control structure

2.3 Experiment Setup

The *FPE* was operated under steady-state conditions: inlet pressure of 1.1 bar (naturally aspirated engine), with the injected fuel mass varied to investigate engine operating speed. Ignition timing was set at 8 mm from the cylinder head. During engine operation, the *FPE* data acquisition system, developed in Lab VIEW software using *NI-USB* 6212, was integrated with a Pico Scope 4425 data logger. A pressure sensor, *AVL-ZF*43 with a Kistler 5010 amplifier, was used to measure in-cylinder combustion pressure. An encoder with a resolution of 0.2 mm/pulse was mounted on the engine to provide data on engine position and speed, Fig. 5.

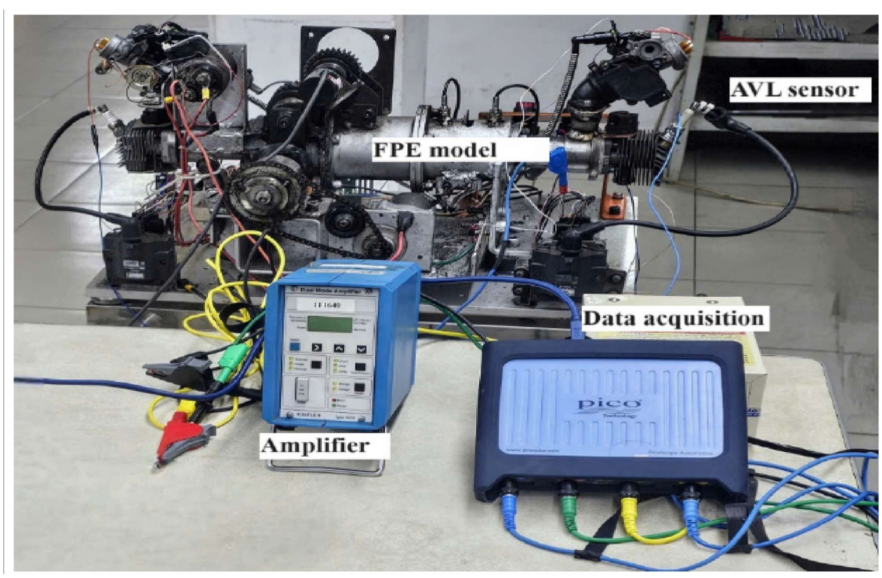

Figure 5. Experimental model of FPE

3. Numerical Modelling

The piston oscillates from the top dead center (*TDC*) to the bottom dead center (*BDC*) or vice versa with a fixed distance of 22mm. The piston can be considered to oscillate in a sinusoidal form, represented as:

$$x_s = A\times(1-\frac{1}{\varepsilon})\sin(2\pi f\times t) \tag{1}$$

Where x_s is the displacement of the piston during engine startup (*mm*), A is the half-stroke length (*mm*), å is the initial compression ratio of the engine at startup, and f is the operating frequency (*Hz*). The mechanical forces acting on the piston include the gas forces in the left and right cylinders, mechanical friction forces, inertia forces, and the driving force of the actuator. The dynamics of the piston can be determined using Newton's Second Law.

$$F_{st} - F_{sl} - F_{sr} - F_f = m\frac{d^2x}{dt^2} \text{ (starting process)} \tag{2}$$

$$F_{cyl} - F_{cyr} - F_f = m\frac{d^2x}{dt^2} \text{ (operation process)} \tag{3}$$

$$F_{cyl} = P_{cyl}\times S \tag{4}$$

$$Fcyr = P_{cyr}\times S \tag{5}$$

F_{cyl} and F_{cyr} are the gas forces generated from the heat release process in the left and right cylinders, respectively. P_{cyl} and P_{cyr} are the pressures in the left and right cylinders, and S is the area of the piston head. F_{sl} and F_{sr} are the friction force, mmm is the mass of the moving part, aaa is the acceleration of the piston, and F_{st} are the compression forces on the left and right sides, respectively. is the force received from the starter device. When the engine transitions to the operating mode, the pressure in the cylinders can be written as follows:

$$P_{cyl} = P_{lcp} + P_{lh}\times \sigma_l \tag{6}$$

$$P_{cyr} = P_{rcp} + P_{rh}\times \sigma_r \tag{7}$$

$$\sigma_l = \begin{cases} 1, & \frac{dx}{dt} \geq 0 \\ 0, & \frac{dx}{dt} < 0 \end{cases}$$

$$\sigma_r = \begin{cases} 1, & \frac{dx}{dt} \geq 0 \\ 0, & \frac{dx}{dt} < 0 \end{cases}$$

P_{lcp}, P_{rcp} are the pressure due to cylinder volume change; P_{lh}, P_{rh} are the pressure due to heat release during combustion.

Application in cylinders can be assessed by the derivative form of the first law of thermodynamics. The simulation will be based on Matlab Simulink software

$$\frac{dp}{dt} = -\gamma.\frac{p}{V}.\frac{dV}{dt} + (\gamma-1)\frac{Q_{in}}{V}\frac{dx_b}{dt} \tag{8}$$

p is in-cylinder pressure (bar); γ is the specific heat ratio; V is in-cylinder volume (m^3); Q_{in} is the input heat energy; x_b is mass fraction burned. The combustion process, which simulates the mass fraction burned, is performed by the Wiebe function [26,27].

$$x_b = 1 - \exp\left[-a\,.\,\left(\frac{t-t_s}{C_d}\right)^{b+1}\right] \tag{9}$$

C_{d-}: is the combustion duration; t_{-s}: is time to start ignition. The constants of a = 5 and b = 2 are used [28]. Simulation based on initial pressure taken from experiment 4 (bar); ignition time at 8 mm from the cylinder head; Linear starting frequency10 Hz, burning time (t-t_s) 2 ms – 5 ms with 100% mass fraction burned. The objective of this model is to simulate the first ignition process through Matlab Simulink software.

4. Simulation and Experimental Results

The simulation and experimental results of piston displacement during the startup process are shown in Fig. 6. It can be observed that the piston displacement curves are similar, with a possible speed reaching 0.7 m/s and a displacement of 22 mm. However, there are discrepancies between the simulation and experimental results, particularly in the piston displacement speed from *TDC* to *BDC* and vice versa. These discrepancies are due to friction losses, assembly errors between mechanical parts, and intake and exhaust gas losses, which were neglected in the simulation.

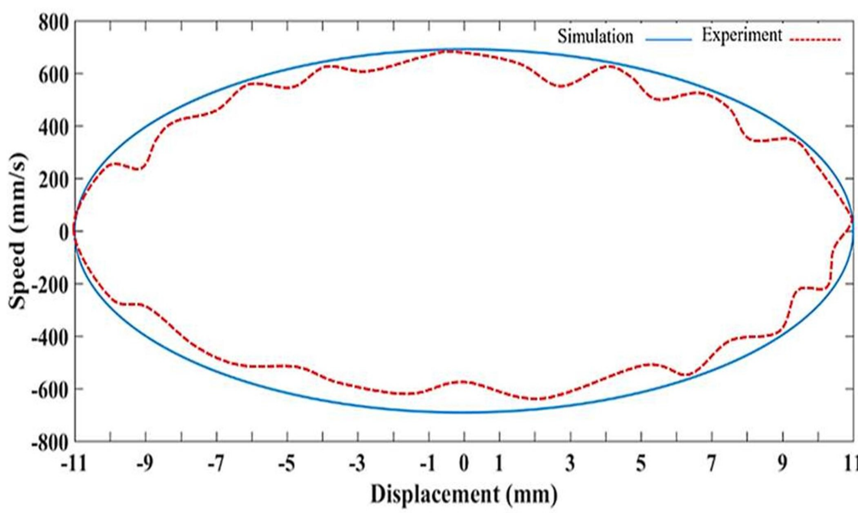

Figure 6. Comparison between simulation and experimental result of displacement and velocity

The cylinder pressure during ignition with a combustion time of 2 ms to 5 ms was simulated and shown in Fig. 7. The peak pressure varies depending on the combustion time; a shorter combustion time results in a higher peak pressure and vice versa. With the initial fuel injection simulated at 3 mg/cycle, the peak pressure ranges from 9 bar to 11 bar, which is greater than the initial compression pressure of 4 bar showed Fig. 10, so it can generate the thrust to move the piston in the opposite direction. TDC is any point where the gas force generated by the heat release exceeds the inertial force from the mechanical starting mechanism.

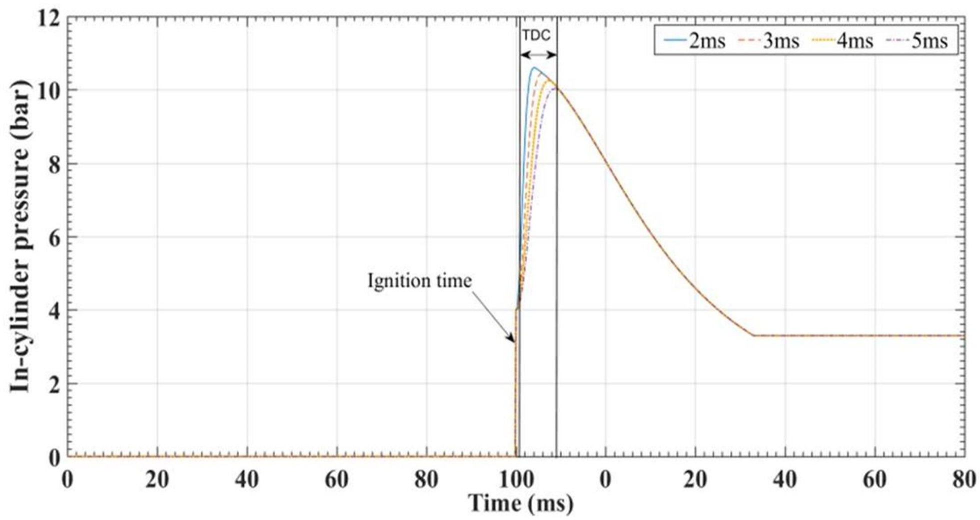

Figure 7. In-cylinder pressure with burn duration time 2 ms -5 ms

The experiments during the first ignition process with fuel injection amounts ranging from 2 mg to 4 mg are shown in Fig. 8. Similar to the simulation, the peak pressure varies in different test runs, despite the same fuel injection volume and ignition timing, as the burn duration time is difficult to control. The pressure during the first ignition can reach 13 bar with a fuel injection of 4 mg. Thus, the pressure from the first ignition is greater than the compression pressure of 4 bar, which is enough to push the piston in the opposite direction and start the engine.

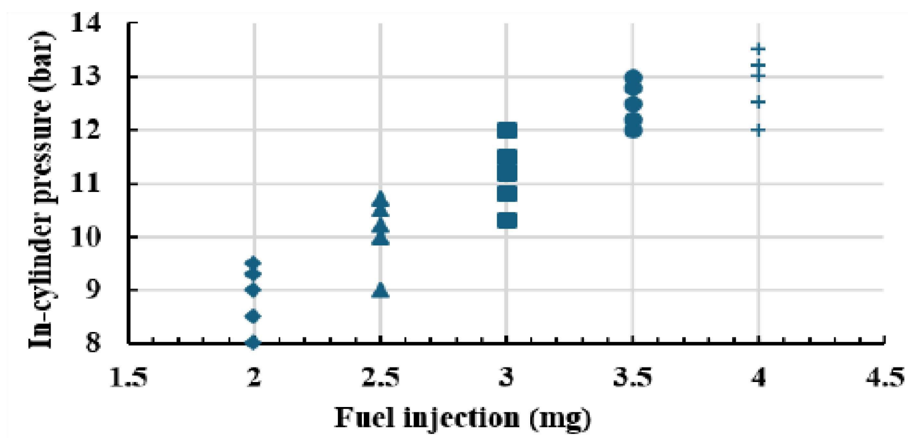

Figure 8. Fuel injection with in-cylinder pressure of the first ignition process

The transition between the starting and operation processes is shown in the Fig. 9. During the first 1.4 seconds, the linear displacement of the piston is 22 mm due to the mechanical starting mechanism being active, making the piston's position relatively stable. In the remaining 0.5 seconds with fule injection 3 mg per cycle, the engine transitions to free operation, during which the piston position becomes unstable, with the highest piston position reaching 30 mm. The maximum engine speed changes from 0.7 m/s to 5 m/s between these two stages.

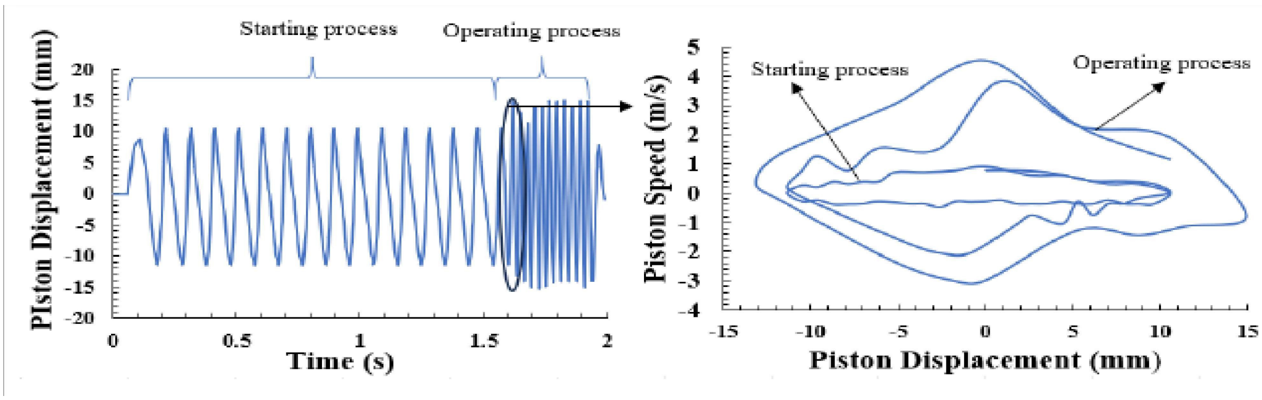

Figure 9. The transition between the starting and operation processes

The changes in peak pressure during these processes are illustrated in Fig. 10. The TDC of the first ignition process and the operation process are different. During the first ignition process, the gas force only needs to exceed the inertia force generated by the starting mechanism for the piston to move in the opposite direction, so TDC is reached before the peak pressure is formed. However, during the running process, the TDC of the FPE is not fixed at one position because the displacement is not controlled by the starting mechanism, leading to pressure during heat release always varying. In this process, the peak pressure coincides with TDC because the gas forces generated from the heat release process must exceed the inertia force create by opposite cylinder.

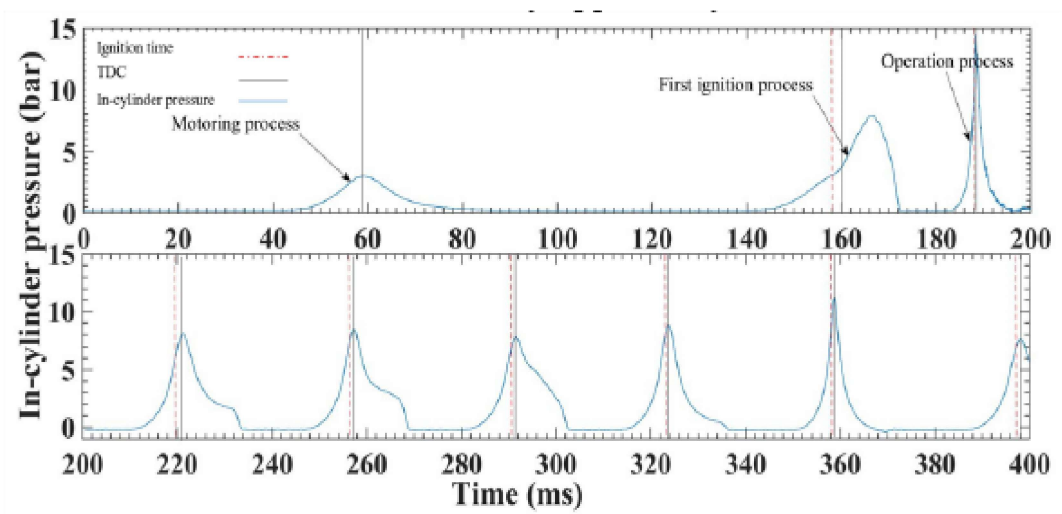

Figure 10. In-cylinder pressure during all processes

There is a certain time interval between the appearance of the spark and the formation of the flame front in an internal combustion engine. This explains why the ignition timing is set at 8 mm during both the startup and operation processes, but the peak pressures of the two processes are different. The peak pressure during the first ignition is lower due to the low initial compression pressure of 4 bar. In the operation process, when the spark appears, the piston is still moving at a speed of 5 m/s, so by the time the flame front forms, the piston has moved to a further position, resulting in a higher initial compression pressure. The piston displacement position during operation varies and depends on the opposing cylinder.

5. Conclusion

This study proposes a dual two-stroke Free Piston Engine (FPE) model using gasoline fuel and spark ignition. Instead of using a linear electric motor as in previous studies, this research developed a mechanical starting mechanism based on the principle of mechanical resonance. A starting controller was developed to operate the piston along a fixed linear trajectory of 22 mm. Based on the proposed structure, the ignition pressure of the first combustion process was modeled and simulated using Matlab Simulink software. The simulation results show that with a starting speed of 0.7 m/s, a starting compression ratio of 3.3, a fuel injection of 3 mg, and a combustion duration of 2 ms to 5 ms, the FPE can ignite with pressures ranging from 9 bar to 11 bar. The mechanical resonance starting method was experimentally validated, achieving the desired compression ratio of 3.3 with a fixed electric motor pull force of approximately 400 N for 1.4 seconds, and a piston displacement speed of about 0.7 m/s. The pressure during the startup process was around 4 bar, and the ignition process produced a peak pressure of 13 bar. The FPE model transitioned to continuous operation over several cycles with peak cylinder pressures reaching 12 bar with a fuel injection of 3 mg.

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